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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Standard Reference Materials:

Second-Surface Mirror Standards of Spectral Specular Reflectance (SRM's 2023, 2024, 2025)

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Second-Surface Mirror Standards of Spectral Specular Reflectance (SRM's 2023, 2024, 2025)

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by

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ABSTRACT

NBS was requested by the Department of Energy to prepare, calibrate and disseminate standards of spectral specular reflectance for use in calibrating reflectometers used to evaluate the solar specular reflectance of concentrating mirrors used in solar energy systems.

The mirror chosen was a second-surface mirror of vacuum-deposited aluminum on optically polished vitreous quartz backed up with a second plate of ground and polished vitreous quartz cemented to the back of the mirror. Standards were prepared in two sizes, 51 x 51 mm, and 25 x 101 mm.

The cost of developing and calibrating the standards was included in a contract issued by the Solar Energy Research Institute of Golden, Colorado, which is financed by the Department of Energy.

Key Words: aluminum mirrors; directional specular reflectance; reflectance specular; reflectance standards; second surface mirrors; solar reflectance; specular spectral reflectance.

Introduction

The Department of Energy requested the National Bureau of Standards to prepare, calibrate and disseminate physical standards of specular spectral reflectance for use in calibrating reflectometers used for evaluating the solar reflectance of collector mirrors used in concentrating solar energy systems. The cost of developing the standards was included in a contract issued by the Solar Energy Research Institute of Golden, Colorado, which is financed by the Department of Energy.

Required Properties

The properties required of the standards relate to the reflectance, size, specularity and durability of the standards.

Reflectance refers to the value of the specular spectral reflectance, the wavelength range over which it is evaluated, and the angle or angles of incidence at which it is evaluated. The spectral range of 250 to 2500 nm was selected for several reasons. The first and most important reason is that the NBS high-accuracy specular spectral reflectometer covers this wavelength range. Most commercial instruments used for specular spectral reflectance measurements are also restricted to this wavelength range. About 98.8 percent of the terrestrial solar irradiance at air mass 1.5 is included in this spectral range. While there is essentially no terrestrial solar irradiance at wavelengths shorter than 300 nm, the inclusion of data from 250 to 300 nm will make the standards more useful in calibrating commerically available spectral reflectometers. The reflectance of the standards should be high, on the order of 90%, over this spectral range. Since the collector mirrors will be used at off-normal angles of incidence of 45° or more, the reflectance of the standards should be evaluated at angles of incidence of at least 30° and 45° from normal.

Size refers to the shape and dimensions of the standards, width, length and thickness. While disc-shaped standards would be useful in some cases, rectangular standards are easier to prepare, and have the advantage of easily determined orientation in use. The normal size of reflectance standards is about 50 mm (2 in) square. If used in an Edwards-type sphere, the width should be no more than 38 mm (1.5 in) and a standard with a width of 25 mm (1 in) may be easier to use. For measuring specular reflectance at large angles of incidence with some instruments a length of 75 mm or more is required. It was decided to prepare standards in two sizes, 51 mm (2 in) square, and 25 x 102 mm (1 x 4 in). There is no special requirement on thickness except that the standard should be thick enough to resist bending and breakage, and not too thick for easy handling. A thickness of about 6 mm (1/4 in) was selected. There is also a requirement that the front and back surfaces of the standard be parallel since the alignment of a sample is determined by contact of the front surface with aligning points in some instruments, and by contact of the back surface in others.

Specularity may be defined as the ratio of the specular reflectance to the hemispherical reflectance. Ideally, this ratio should be one with none of the incident flex reflected in directions other than the specular direction. This cannot be attained experimentally, but it has been closely approached by these standards, as will be discussed later.

Durability refers to the ability of the standard to retain its calibration value indefinitely. The three mechanisms that cause the reflectance of the standard to change with time are 1) physical damage, primarily abrasion, 2) chemical corrosion such as oxidiation or tarnish, and 3) surface contamination. The standard should have a hard surface to resist abrasion, be chemically inert or suitably protected to resist chemical corrosion, and easily cleanable to permit surface contamination to be removed and the initial reflectance restored.

Mirror Types and Materials

Specular reflectors of high reflectance are almost always optically smooth metallic surfaces. Such surfaces can be prepared by optically polishing massive metal, or by vacuum deposition or sputtering of a thin opaque layer of metal on a polished substrate.

Mirrors are of two types, first surface and second surface. In a first-surface mirror the metal surface is directly exposed to the atmosphere, so that the incident rays hit the metal directly. In a second-surface mirror the metal surface has a protective layer between it and the atmosphere. This protective layer may be a thin sheet of optically polished transparent material, such as glass, to which a thin film of the reflecting metal is applied, or a thin film of metal applied to an opaque substrate and covered with a second layer of a protective transparent material. In a second-surface mirror the incident rays pass through the protective layer before and after reflection. The transmitting layer, called the superstrate, can be designed to have good resistance to abrasion, to be impermeable to protect the metal against chemical corrosion, and easily cleanable so that surface contamination can be removed without affecting the reflecting layer. In addition, most heliostat mirrors are second surface mirrors, and can be best simulated by a second surface mirror standard. For these reasons, a second-surface mirror was selected for use as the standard.

Three metals have reasonably high reflectance in the solar range, aluminum, rhodium and silver. Both aluminum and silver are soft, and not very resistant to abrasion. Rhodium is much harder and more resistant to abrasion. It would be the best of the three metals for a first-surface mirror, since it is also chemically inert. Its reflectance is low compared to that of silver and aluminum. This, combined with its high cost and the difficulty in obtaining good adhesion of a vacuum-deposited layer to a polished substrate make it unsuitable for use as a second surface mirror standard. Previous experience at NBS

indicates that it is difficult to produce first surface rhodium mirrors with uniform reflectance over the surface of a single 50 x 50 mm sample. Both aluminum and silver are suitable for use as the reflecting layer in a second-surface mirror.

A large majority of the concentrating mirrors used in solar energy systems consist of wet chemical reduction silver on glass. While the wet chemical reduction process has a long history of use in the manufacture of mirrors, the application process is still something of an art. The detailed chemistry of the reduction process, and particularly the factors that must be controlled and the specific conditions required to produce a high-reflectance adherent coating on glass are not known with sufficient accuracy to assure reliable production of such flims. In addition, the reflectance of silver, while very high at wavelengths above about 500 nm, drops abruptly below 400 nm to a value near zero at about 320 nm.

Aluminum is used for some first surface concentrating mirrors, in the form of polished metal, either sheet or foil, and as a vacuum deposited film on a plastic substrate. The reflectance of aluminum is only slightly lower than that of silver at wavelengths longer than about 1000 nm, and is much higher than that of silver at wavelengths below 400 nm. There is a broad shallow absorption peak at about 825 nm, where the reflectance drops below 90%. Aluminum is easily applied by vacuum deposition, and adheres readily to most substrates. The factors affecting the deposition process are well known, and can be easily controlled. For these reasons aluminum was selected as the reflecting layer of the second surface mirror standards.

Optical quality polished vitreous quartz is significantly harder than glass, and hence more resistant to abrasion. It has high transmittance over a wider wavelength range than glass, particularly in the ultraviolet. Because of its hardness, it is easier to produce an optical polish on fused quartz than on glass. Typical values of rms roughness of optically polished materials are listed in [1] as 4.1 nm for flint glass, 1.8 nm for plate glass, 1.4 nm for Pyrex glass, 0.96 nm for fused quartz and 0.27 nm for bowl polished fused quartz.

The reflectance of a surface for normal incidence is reported in [1] to be related to the rms roughness, σ, and rms slope, m, by the equation

$$R_s = R_o . \exp\left[-(4\cdot\pi\cdot\sigma)^2/\lambda^2\right] + R_o \frac{2^5\cdot\pi^4}{m^2} \cdot (\sigma/\lambda)^4\cdot(\Delta\theta)^2 \qquad (1)$$

where R_s is the reflectance of a sample measured for normal incidence with an instrument of acceptance angle $\Delta\theta$. When $\sigma \ll \lambda$, the second term becomes negligible, and may be omitted. The first term is for the reduction in specular reflectance due to diffraction, and the second term is the loss due to diffusely reflected light.

Vacuum Deposited Aluminum

Hass [2] reports "It is well known that the optical properties of all evaporated films are strongly influenced by many factors, such as speed of deposition, pressure during the evaporation, thickness of the coating, temperature of the substrate, and aging in air."

Vacuum deposited aluminum is highly reactive, and oxidizes on exposure to air. The oxide forms a transparent tightly adherent layer of low permeability to oxygen, which protects the aluminum against further oxidation. This oxide layer accounts for the excellent resistance of aluminum to atmospheric corrosion. The rate at which the aluminum oxidizes, the thickness of the coating eventually formed, and the time required to reach the maximum thickness are strongly influenced by the purity of the aluminum, its compactness, the pressure (vacuum) during evaporation, the speed of evaporation, and conditions, such as temperature and humidity, during aging. Hass [3] describes a method of applying pure (99.99%) aluminum in a vacuum of 1×10^{-5} torr at a deposition rate of 50 nm per second. A shutter in front of the samples protects substrates against contamination during outgassing of the evaporation sources and their charges. The shutter is opened when the evaporation reaches constant speed, and is closed when a film of the desired thickness is obtained. This method was used by Bennett et al [4] for the preparation of samples for the evaluation of the reflectance of aluminum. They found that films prepared by this procedure had higher reflectances than those prepared in the optics shop at their facility, where a vacuum of 1×10^{-4} torr was used, and where deposition rates were on the order of 5 nm per second. The main differences in the reflectances occurred in the ultraviolet and visible portions of the spectrum. Hass [3] shows graphs of the effect of pressure and deposition time on the reflectance of aged vacuum deposited aluminum.

Earlier work at NBS, about 1968-1971, showed that the ultraviolet reflectance of first-surface mirrors of vacuum deposited aluminum, prepared for NBS by a commercial coating laboratory, continued to decrease over a period of over one year. The samples were allowed to age for over two years, in order to be sure that the reflectance had reached a stable value, before calibration as specular spectral reflectance standards.

Bennett et al. [5] prepared vacuum deposited films of aluminum at a pressure of 1×10^{-10} torr, and found that the reflectance of these films measured in an atmosphere of dry nitrogen, was about 1% higher than that of aged samples coated in a vacuum of about 1×10^{-5} torr.

A brief search of the literature for data on the stability of the reflectance of second-surface mirrors of vacuum-deposited aluminum proved fruitless. From the known properties of aluminum it is believed that the second-surface mirrors will be highly stable in reflectance. The aluminum was deposited by the procedure described by Hass [3], and hence the aluminum at the quartz-aluminum interface should be free from

contamination due to the evaporation process. This interface is protected against oxidation by the optical quality vitreous quartz on the front, and by five, and perhaps six, separate layers on the back. The aluminum was deposited to a thickness of about 150 nm, about three times the thickness required for an opaque coating. A protective layer of silicon monoxide was deposited on top of the aluminum before it was removed from the vacuum chamber, followed by a second coat of aluminum and a second coat of silicon monoxide. If any oxygen penetrated the silicon monoxide coating, it immediately formed a layer of aluminum oxide beneath the silicon monoxide. A backing plate of vitreous quartz was cemented to the back of the aluminum coating, on top of the second silicon monoxide layer.

Manufacture of Standards

The standards were manufactured in the NBS Optical Shop. The top plate, to which the reflective coating of aluminum was later applied, was of optical quality vitreous quartz, ground to a thickness of 2 mm, and polished on both sides. A bowl polishing technique was used, which produced an AA roughness of about 0.7 nm. The two sides of each plate were flat to within one fringe and parallel to within 0.01 mm.

The preparation of the standards was supervised by Edward P. Muth, Chief of the NBS Optical Shop. Grinding and polishing of the plates and cementing of the mirrors was done by John E. Fuller, and the coating was done by David B. Wilmering.

The base plate was similarly of vitreous quartz, ground to a thickness of 3.7 mm, with a fine ground finish on one side and an optical polish on the other.

The plates, both top and base, were thoroughly cleaned before coating. The cleaning procedure consisted of 1) hand scrubbing with a warm solution of detergent, followed by a rinse in warm tap water, 2) a rinse with distilled water immediately following the tap water rinse, 3) degreasing in an alcohol degreaser, in which the surface was rinsed with freshly distilled alcohol, 4) a light scrub with absorbent cotton and CP acetone, followed by an acetone rinse. The plates were then subjected to a critical visual inspection, and those showing any sign of a residual deposit were recleaned. The first operation in the coating chamber consisted of a corona discharge cleaning, which was the final cleaning.

The coating chamber has a shutter that completely covers the plates during evacuation and the first stage of evaporation of aluminum. The deposition of aluminum was started with the shutter closed. After the chamber was completely filled with aluminum vapor, the shutter was opened, and a layer of high-purity aluminum was applied to a thickness of 150 nm in a period of about 5 seconds. The thickness of the aluminum coating was monitored during application with a quartz crystal thickness

gage. An overcoating of a half wavelength of silicon monoxide was applied over the aluminum before the vacuum was broken. The silicon monoxide coating inhibits oxidation of the aluminum when exposed to air.

Careful visual examination of the first few mirrors prepared by the above procedure revealed the presence of a few scattered pinholes in the aluminum coating that were readily visible when the mirror was held up to the sun or a strong light. The reflectance of areas of the same mirror with and without pinholes was measured with a reflectometer with an uncertainty of 0.002 in reflectance, but no difference could be detected. Measurements of the transmittance of an area containing pinholes were made with equipment that can measure transmittance of 0.001, but no transmittance was detected. On the basis of the above measurements the pinholes were considered to be a cosmetic defect. However, the aluminum coating was removed and the mirrors were recoated following a modified procedure.

The modified procedure included the application of a first coat of aluminum and silicon monoxide as described above, followed by second coatings of aluminum and silicon monoxide, applied without breaking the vacuum. In addition, a single similar coat of aluminum and silicon monoxide was applied to the polished face of the backing plate.

The coated sides of the two plates were cemented together with an epoxy optical cement, in a jig that held the two sides of the finished standard parallel to about 0.01 mm.

The complete standard is about 5.8 mm thick, with a highly polished surface that is easily cleaned on the front (reflecting) surface, and a fine ground finish on the back, so that the calibrated surface can be easily identified. The flat standards were made in sizes of 51 x 51 mm, and 25 x 101 mm, and are designated as SRM's 2023 and 2024 respectively.

A few samples in the 25 x 101 mm size were prepared with both top and bottom plates tapered with an included plane angle of 10 mrad. These samples were also cemented by use of a jig, to keep the top and bottom surfaces of the finished mirror parallel to 0.01 mm. The reflected beams from the vitreous quartz first surface and the aluminum second surface thus diverge by about 20 mrad, and can be separately distinguished and measured if there is sufficient distance between the mirror and the detector.

The specular reflectance of an uncoated top plate was measured with the NBS high accuracy specular reflectometer, at an angle of incidence of 6° from normal. The total reflectance of each tapered mirror at an angle of incidence of 6° from normal was measured on the high-precision integrating sphere reflectometer. The values for these two measured reflectances, and the values of reflectance for the reflected beams from the vitreous quartz first surface and the aluminum second

surface, computed from the measured values, will be supplied with the tapered mirrors, which are available for sale as SRM 2025.

Calibration of the Master Standards

Calibration of the two master standards was accomplished by measurements on the NBS Reference Specular Reflectometer-Spectrophotometer [6]. This instrument measures specular reflectance by absolute techniques. The measurements are made as a function of wavelength, angle of incidence, and polarization.

In calibrating the master second surface mirrors, the instrument was operated with a spectral pass band of 10 nm. The collimated incident beam had a cross section of 18 mm x 12 mm at the sample. The incident beam was polarized either parallel or normal to the plane of incidence. The sample or test mirror was mounted on a turntable. The surface of the mirror and the axis of rotation of the turntable occupied a common vertical plane, thus making it possible to vary the angle of incidence. A complete description of these measurement procedures and a more detailed explanation of the mechanics of the specular reflectometer is given in the accompanying reprint documenting that instrument.

The calibration of the master mirrors was made at 50 nm intervals from 250 to 900 nm, at 100 nm intervals from 900 to 1300 nm, at 250 nm intervals from 1500 to 2500 nm, and at the laser wavelengths 632.8 and 1060 nm. The total time required to complete these calibrations was approximately 25 hours of instrument running time per mirror. The measurements were made at each wavelength for both vertically (S) and horizonally (P) polarized incident beams and at three angles of incidence. The measurements were repeated six times for each of these conditions. Three of the six measurements were made with the angles of incidence set by rotating the mirror clockwise from the normal, and the other three measurements were made with the angles of incidence set by rotating the mirror counterclockwise from the normal. The final reflectance value is an average of these six measured values for a given polarization, angle of incidence, and wavelength setting.

The overall uncertainties in the calibration of the master standards are believed to be on the order of ±0.2%. This uncertainty is based on an analysis of the known uncertainties in the performance of the Reference Spectrophotometer [7] and the specular reflectometer.

Calibration of the Standard Reference Material 2023 and 2024 Second Surface Mirrors

Because of the time required to calibrate a mirror on the Reference Specular Reflectometer-Spectrophotometer and the cost of such calibrations it was necessary to resort to less time consuming techniques in order to transfer the absolute reflectance scale from the master mirror to the remainder of the second surface mirrors that would eventually be

issued as Standard Reference Materials. The calibration of these mirrors was accomplished by direct comparison of each mirror with the master mirror at each of the 25 wavelengths for which the master mirror was previously calibrated. This comparison was made on a commercial spectrophotometer equipped with an integrating sphere reflectometer. The comparison was made for 6° incidence only, because of the fixed geometry of the commerical reflectometer. The absolute reflectance for 6° incidence of each of the Standard Reference Material mirrors was obtained directly by setting the photometric scale of the spectrophotometer with the master mirror so that the recorder reading matched the corresponding absolute reflectance value of the master mirror at a given wavelength setting. The master was then replaced by a test mirror and the recorded value of its reflectance was read directly from the photometric scale. The direct reading obtained by this procedure required no further corrections. The master mirror reflectance was checked before and after measuring each test mirror in order to detect any drifting of the photometric scale.

Calibration of Wedge Standards

The specular spectral reflectance of a master second-surface mirror was measured at 25 wavelengths with the NBS high-accuracy specular spectral reflectometer at 6° incidence. The first surface reflectance, ρ_1, of an uncoated cover plate was also measured with the same instrument at 6° incidence, with a receptor that received only the beam reflected from the first surface. The 6°-hemispherical reflectance of each wedge standard was compared to that of the master standard at the same 25 wavelengths with a high-precision integrating sphere reflectometer. The measured reflectance ratio was multiplied by the known reflectance of the standard at each wavelength to obtain the ρ_t spectral data reported in Table 1.

All of the cover plates were cut from a single piece of optical quality vitreous quartz and had identical polishing treatment. It is assummed that the reflectance of the first surface of the cover plates is the same as that of the measured uncoated cover plate, within the uncertainty of the measured value.

Since the cover plate is a wedge with an included plane angle of 10 mrad, it acts as a prism of low dispersing power. The index of refraction of the cover plate, at each wavelength, was computed from the measured first surface reflectance by use of the equation for reflectance at normal incidence,

$$\rho_N = \left(\frac{n-1}{n+1}\right)^2 \quad . \tag{2}$$

TABLE 1

Measured Total Specular Spectral Reflectance, for 6° Incidence, of Wedge Standards and First Surface Reflectance of Fused Silica Cover Plate

Wavelength λ nm	Standard Number 95w	96w	97w	98w	99w	100w	101w	102w	103w	105w	106w	107w	cover plate
250	0.869	0.869	0.867	0.867	0.866	0.867	0.865	0.869	0.862	0.862	0.875	0.869	0.0406
300	.895	.896	.895	.895	.896	.896	.895	.896	.896	.893	.895	.894	.0379
350	.895	.895	.895	.894	.895	.895	.895	.895	.894	.894	.894	.895	.0364
400	.893	.895	.894	.893	.893	.894	.893	.894	.893	.892	.892	.893	.0355
450	.888	.891	.888	.888	.889	.889	.888	.888	.888	.888	.888	.888	.0350
500	.884	.887	.885	.885	.885	.885	.885	.885	.885	.885	.885	.884	.0347
550	.879	.880	.880	.879	.879	.880	.879	.879	.879	.879	.878	.878	.0344
600	.874	.875	.874	.873	.874	.875	.873	.874	.874	.873	.873	.874	.0342
632.8	.869	.870	.868	.868	.869	.868	.868	.868	.868	.869	.868	.868	.0342
650	.865	.866	.866	.865	.865	.866	.865	.865	.865	.865	.865	.865	.0342
700	.853	.854	.854	.853	.853	.854	.853	.853	.853	.852	.853	.853	.0339
750	.834	.835	.835	.834	.835	.835	.834	.834	.835	.834	.834	.835	.0338
800	.807	.808	.807	.807	.807	.808	.807	.807	.807	.806	.807	.807	.0337
850	.799	.803	.801	.800	.801	.801	.800	.801	.800	.800	.800	.800	.0335
900	.847	.848	.847	.847	.847	.847	.847	.847	.847	.847	.847	.847	.0334
1000	.911	.911	.911	.911	.911	.911	.911	.911	.911	.910	.910	.911	.0333
1060	.925	.926	.926	.925	.925	.925	.925	.925	.924	.924	.924	.925	.0332
1100	.933	.933	.933	.933	.933	.933	.933	.932	.932	.932	.932	.932	.0332
1200	.942	.942	.942	.942	.942	.942	.942	.942	.942	.942	.942	.942	.0330
1300	.947	.947	.947	.947	.947	.947	.947	.947	.947	.947	.947	.947	.0328
1500	.952	.952	.952	.952	.952	.952	.952	.952	.952	.952	.952	.952	.0325
1750	.955	.955	.955	.955	.955	.955	.955	.955	.955	.955	.955	.955	.0321
2000	.955	.955	.955	.955	.955	.955	.955	.955	.955	.955	.955	.955	.0317
2250	.948	.951	.951	.951	.948	.948	.951	.950	.951	.948	.948	.951	.0313
2500	.946	.946	.950	.948	.948	.948	.950	.950	.947	.948	.948	.949	.0310

The solution for index of refraction, n, as a function of ρ_N is

$$n = \frac{1+\sqrt{\rho_N}}{1-\sqrt{\rho_N}} \quad . \tag{3}$$

The reflectance of vitreous quartz at 6° incidence is higher than that at normal incidence by less than 0.000005, hence the error introduced by using equation (3) is considered negligibly small. The indices of refraction for the 25 wavelengths at which reflectance measurements were made are given in Table 2.

The angles of reflection for the first four beams reflected from each standard were computed for each wavelength from the index of refraction. The plane of incidence is taken as a plane normal to the surface and parallel to the long sides of the standard. All angles toward the thin end of the wedge are negative, and those toward the thick end are positive.

The direction θ_1 of the first beam, with reflectance ρ_1, is 6° since there is no refraction. The portion $(1-\rho_1)$ of the incident beam that penetrates the cover plate is refracted at angle θ_2

$$\theta_2 = \sin^{-1}[\sin\theta_1/n] \tag{4}$$

where θ_1 is -6° (there is a sign change on reflection or refraction) and is incident on the second surface at an angle of $-(\theta_2+\alpha)$ where α is the included plane angle of the wedge. The beam is reflected at the second surface and is incident on the first surface at an angle of $-(\theta_2+2\alpha)$. The emergent beam, with reflectance ρ_2, will be refracted at angle θ_3

$$\theta_3 = \sin^{-1}\left\{ n \sin\ [2\alpha + \sin^{-1}(\sin\theta_1/n)]\right\} \quad . \tag{5}$$

In like manner the beam, with reflectance ρ_3, that is internally reflected by the first surface and reflected a second time by the second surface will be refracted at an angle θ_4.

$$\theta_4 = \sin^{-1}\left\{ n \sin\ [4\alpha + \sin^{-1}(\sin\theta_1/n)]\right\} \quad , \tag{6}$$

and the beam with reflectance ρ_4 reflected internally twice by the first surface and three times by the second surface will be θ_5

$$\theta_5 = \sin^{-1}\left\{ n \sin\ [6\alpha + \sin^{-1}(\sin\theta_1/n)]\right\} \quad . \tag{7}$$

Essentially all of the flux reflected from a wedge standard is contained in the first four reflected beams. The directions, in degree from normal for the first four beams reflected by a wedge standard from a collimated beam incident at -6° are given in Table 2.

Note that the angle of reflection is a function of both the wedge effect of the cover plate and its dispersion. The wedge effect is independent of wavelength. The dispersion angle changes with wavelengt because the index of refraction of the cover plate changes with wavelength. If the wedge standards are used to calibrate a specular spectral reflectometer at different wavelengths, using beam 2 reflected once from the second-surface aluminum coating, the dispersion effect may make it necessary or desirable to shift the optical path slightly when changing wavelength. If spectrally total reflectance measurements are made, there will be a slight spread (about 0.1° for beam 2, 0.2° for beam 3 and about 0.35° for beam 4) in the reflected beam, due to the dispersion of the cover plate, and a slightly larger detector may be required for spectrally total measurements than for spectral measurement.

The total specular reflectance, ρ_t, of a wedge standard can be closely approximated in terms of the reflectance, ρ_1, of the first surface, the transmittance, τ_1 (= 1 - ρ_1) of the first surface, and the internal reflectance ρ_s of the second surface, as the infinite series

$$\rho_t = \rho_1 + \tau_1^2 \cdot \rho_s + \tau_1^2 \cdot \rho_1 \cdot \rho_s^2 + \tau_1^2 \cdot \rho_1^2 \cdot \rho_s^3 + \tau_1^2 \cdot \rho_1^3 \cdot \rho_s^4 --- \quad . \quad (8)$$

Rearranging and collecting terms, we set

$$(\rho_t - \rho_1)\rho_1 = \tau_1^2[\rho_1 \cdot \rho_s + (\rho_1 \cdot \rho_s)^2 - (\rho_1 \cdot \rho_s)^3 + (\rho_1 \cdot \rho_s)^4 \; - -] \; , \quad (9)$$

$$(\rho_t - \rho_1) = \frac{\tau_1^2 \cdot \rho_s}{1-\rho_1 \cdot \rho_s} \quad . \quad (10)$$

Solving for ρ_s,

$$\rho_t - \rho_1 = \rho_s[\tau_1^2 + \rho_t \cdot \rho_1 - \rho_1^2] \quad ,$$

$$\rho_s = \frac{\rho_t - \rho_1}{\tau_1^2 + \rho_t \cdot \rho_1 - \rho_1^2} \quad . \quad (11)$$

The reflectances, ρ_2, for the beam reflected once from the second surface, ρ_3 for the beam reflected twice from the second surface, and ρ_4 for the beam reflected three times from the second surface, can be computed from the measured values of ρ_t and ρ_i as

POSITION DESCRIPTION *(Please Read Instructions on the Back)*

1. Agency Position No.: 41120008

2. Reason for Submission: [ ] Redescription [ ] New [ ] Reestablishment [X] Other
Explanation (Show any positions replaced): Promotion

3. Service: [X] Dept'l [ ] Field

4. Employing Office Location: Gaithersburg, Md

5. Duty Station: Gaithersburg, Md

6. CSC Certification No.:

7. Fair Labor Standards Act: [ ] Exempt [X] Nonexempt

8. Employment/Financial Stmt Required: [ ] Yes [X] No

9. Subject to IA Action: [ ] Yes [X] No

10. Position Status: [X] Competitive [ ] Excepted (Specify)

11. Position is: [ ] Supvrsy [ ] Managerial [X] Neither

12. Sensitivity: [ ] Critical [ ] Noncritical [X] Nonsensitive

13. Competitive Level Code: 123

14. Agency Use:

15. Classified/Graded by	Official Title of Position	Pay Plan	Occupational Code	Grade	Initials	Date
a. Civil Service Commission						
b. Department, Agency, or Establishment	Secretary (Typing)	GS	0318	05	nlo	10-23-84
c. Bureau						
d. Field Office						
e. Recommended by Supervisor or Initiating Office	Secretary (Typing)	GS	0318	05		

16. Organizational Title of Position (if different from official title):

17. Name of Employee (if vacancy, specify): Vickie J. Fields

18. Department, Agency, or Establishment: U.S. Department of Commerce

a. First Subdivision: National Bureau of Standards

b. Second Subdivision: Inst for Computer Sciences & Technology

c. Third Subdivision: Center for Computer Systems Engineering

d. Fourth Subdivision: System Components Division

e. Fifth Subdivision:

19. Employee Review. *This is an accurate description of the major duties and responsibilities of my position*

Signature of Employee *(optional)*

20. Supervisory Certification. *I certify that this is an accurate statement of the major duties and responsibilities of this position and its organizational relationships, and that the position is necessary to carry out Government functions for which I am responsible. This certification is made with the knowledge that this information is to be used for statutory purposes relating to appointment and payment of public funds, and that false or misleading statements may constitute violations of such statutes or their implementing regulations.*

a. Typed Name and Title of Immediate Supervisor: D.K. Branstad, Mgr., Security, Speech I/O, & Integrity Program

Signature: Dennis K. Branstad — Date: 10/11/84

b. Typed Name and Title of Higher-Level Supervisor or Manager (optional): John P. Riganati, Chief 652

Signature: [signature] — Date: 84/10/11

21. Classification/Job Grading Certification. *I certify that this position has been classified/graded as required by Title 5, U.S. Code, in conformance with standards published by the Civil Service Commission or, if no published standards apply directly, consistently with the most applicable published standards.*

Typed Name and Title of Official Taking Action: Vickie L. Southers, Personnel Management Specialist

Signature: Vickie L. Southers — Date: 10-23-84

22. Standards Used in Classifying/Grading Position: GS-318 dated January 1979

Information for Employees. The standards, and information on their application, are available in the personnel office. The classification of the position may be reviewed and corrected by the agency or the Civil Service Commission. Information on classification/job grading appeals, and complaints on exemption from FLSA, is available from the personnel office or the Commission.

23. Position Review	Initials	Date	Initials	Date	Initials	Date	Initials	Date	Initials	Date
a. Employee (optional)										
b. Supervisor										
c. Classifier										

24. Remarks

25. Description of Major Duties and Responsibilities *(see attached)*

$$\rho_2 = \tau_1{}^2 \cdot \rho_s \quad , \tag{12}$$

$$\rho_3 = \tau_1{}^2 \cdot \rho_s{}^2 \cdot \rho_1 \quad , \tag{13}$$

$$\rho_4 = \tau_1{}^2 \cdot \rho_s{}^3 \cdot \rho_1{}^2 \quad . \tag{14}$$

The computed values for ρ_2, ρ_3, and ρ_4 of a typical wedge standard are given in Table 3, together with the measured values of ρ_t and ρ_1, and the sum of ρ_1, ρ_2, ρ_3 and ρ_4. It is interesting to note that the sum of the reflectances for the four beams is less than the measured ρ_t by about 0.00003 reflectance units which provides an internal check of the validity of the computations, and also shows that the fraction of the reflected flux in all beams beyond the fourth is negligibly small.

Equations 8 through 14 are derived on the basis of two assumptions; 1) that there is no internal absorption in the vitreous silica, and 2) that the values of τ_1, ρ_1 and ρ_s are independent of the angle of incidence over the range of angles of incidence involved. There is some slight absorption in the vitreous silica at 250 nm, and at this wavelength the absorptance appears in the computed value of ρ_s, which is the product of the true ρ_s and the square of the transmittance of the vitreous silica. For the thin layer of vitreous silica involved, the internal absorptance at wavelengths from 300 to 2500 nm is negligibly small. The reflectances ρ_1 and ρ_s are essentially independent of the angle of incidence for angles of incidence of up to 15° from the normal to the surface. The reflectance for a material with index of refraction of 1.5 is 0.040000 at normal incidence, and 0.04000198 at 15° incidence. The fractional error due to the assumption that the reflectance is independent of the angle of incidence is thus 0.0000495 at 6° incidence, and 0.002019 at 15°, which is well within the uncertainty of the measured values.

Uncertainties

At some wavelengths, the instrument noise of the commercial spectrophotometer was slightly greater than ±0.2%. Therefore the final uncertainty for the Standard Reference Material mirrors (the sum of the uncertainty for the master standard and that for the measured mirror) was increased to ±0.5%. This uncertainty is larger than the ±0.2% assigned to the master through the more accurate determinations made on the Reference Specular Reflectometer. However, the uncertainty of ±0.5% is probably realistic for the Standard Reference Material mirrors. Uncertainties less than ±0.5% cannot be guaranteed without careful absolute techniques.

TABLE 3

Reflectances for Wedge Standard 95W

λ nm	ρ_1	ρ_t	ρ_s	ρ_2	ρ_3	ρ_4	$\sum \rho_1-\rho_4$
250	.0406	.869	0.8683	0.7992	0.0282	0.0010	0.86896
300	.0379	.895	.8946	.8280	.0281	.0010	.89497
350	.0364	.895	.8946	.8306	.0270	.0009	.89497
400	.0355	.893	.8926	.8303	.0263	.0008	.89297
450	.0350	.888	.8875	.8265	.0257	.0008	.88797
500	.0347	.884	.8835	.8233	.0252	.0008	.88398
550	.0344	.879	.8785	.8191	.0248	.0007	.87898
600	.0342	.874	.8734	.8147	.0243	.0007	.87398
632.8	.0342	.869	.8684	.8100	.0241	.0007	.86898
650	.0342	.865	.8644	.8062	.0238	.0007	.86498
700	.0339	.853	.8522	.7954	.0230	.0007	.85298
750	.0338	.834	.8330	.7777	.0219	.0006	.83398
800	.0337	.807	.8057	.7523	.0204	.0006	.80698
850	.0335	.799	.7976	.7450	.0199	.0005	.79899
900	.0334	.847	.8462	.7906	.0223	.0006	.84698
1000	.0333	.911	.9107	.8511	.0258	.0008	.91098
1060	.0332	.925	.9248	.8644	.0265	.0008	.92497
1100	.0332	.933	.9328	.8719	.0270	.0008	.93297
1200	.0330	.942	.9419	.8807	.0274	.0009	.94197
1300	.0328	.947	.9469	.8858	.0275	.0009	.94697
1500	.0325	.952	.9519	.8911	.0276	.0009	.95197
1750	.0321	.955	.9549	.8946	.0274	.0008	.95497
2000	.0317	.955	.9549	.8954	.0271	.0008	.95497
2250	.0313	.948	.9479	.8895	.0264	.0008	.94798
2500	.0310	.946	.9459	.8882	.0260	.0008	.94598

The values for ρ_1, the first surface reflectance, and ρ_t, the total reflectance for all beams are certified measured values. The reflectances ρ_s for the internal reflectance at the vitreous quartz-aluminum interface and the reflectances ρ_2. ρ_3 and ρ_4 are computed from the measured values, and are not certified.

An every-day working standard can be calibrated relative to the Standard Reference Material mirror by the user for situations in which the standard must be handled often. This will help to preserve the Standard Reference Material mirror for periodic control of the measurement process.

Cleaning

It is recommended that the Standard Reference Material mirror be cleaned with isopropyl alcohol followed by a rinse with distilled water.

The Certificates of Calibration

The second-surface aluminum mirrors in which the reflecting surface is parallel to the front surface have been designated Standard Reference Materials 2023 and 2024. A copy of the certificate is included here for general information. The spectral specular reflectance of the mirrors in the wavelength range 250 to 2500 nm is shown in the graph on page 2. The wavelength scale is greatly compressed and the photometric scale expanded in this graph, hence the absorption feature at approximately 800 nm is emphasized. The small absorption features near 1400 and 2000 nm are absorption features of the vitreous-quartz plate that protects the aluminum coating. The data in Table 1 of the certificate are valid for 6° incidence only. However, they are useful for other angles of incidence near normal for essentially unpolarized sources. The data given in Table 2 of the certificate are uncertified but represent a typical second-surface aluminum mirror. They show that the reflectance of the mirrors for the unpolarized incident beam does not vary significantly for angles of incidence up to 45°. The variation in reflectance with angle of incidence may be significant for polarized incident beams depending on the wavelength.

The wedge mirrors, in which the reflecting surface is at an angle of 10 mrad to the front surface in a direction parallel to the long dimension, have been designated Standard Reference Material 2025. A copy of the certificate for these standards is also included for general information. The measured values of ρ_1, the specular spectral reflectance of the first surface of the optically-polished vitreous quartz cover plate, and ρ_t, the total specular spectral reflectance for all beams, are certified. The computed values for the reflectances of the first three beams reflected from the aluminum surface, and the directions for these beams, are not certified.

U.S. Department of Commerce
Malcolm Baldrige
Secretary

National Bureau of Standards
Ernest Ambler, Director

National Bureau of Standards

Certificate

Standard Reference Material 2023

Second Surface Aluminum Mirror for Specular Reflectance from 250 to 2500 nm

V. R. Weidner and J. J. Hsia

This Standard Reference Material (SRM) is intended for use in calibrating the photometric scale of specular reflectometers. SRM 2023 is 5.1 x 5.1 cm in size. The aluminum mirror is vacuum deposited on the surface of a 2-mm thick fused-quartz plate. This mirror is protected by a second fused-quartz plate attached to the first plate with epoxy cement.

The specular reflectance of the mirror was measured at 50-nm intervals from 250 nm to 900 nm, at 100-nm intervals from 900 nm to 1300 nm; and at 250-nm intervals from 1500 nm to 2500 nm. In addition to these wavelengths, the reflectance was also measured at the laser wavelengths 632.8 nm and 1060 nm.

The certified values were determined in the following way: The reflectance of a master mirror was measured at the above specified wavelengths with a highly accurate specular reflectometer-spectrophotometer at angles of incidence of 6°, 30°, and 45°. These measurements were made for both vertically and horizontally polarized incident beams. The overall uncertainty of these measurements is ±0.2 percent. The specular reflectance of the SRM second surface mirror was measured relative to the master mirror on a high-precision reflectometer for 6° incidence only. The certified values of specular reflectance for the SRM mirror is based on the average value of the vertical and horizontal polarizations for the master mirror at 6° incidence. The certified values listed in Table 1 are assigned an uncertainty of ± 0.005. The uncertified data listed in Table 2 indicate the variation in the specular reflectance of a typical second surface SRM mirror as a function of angle of incidence and plane of polarization. Figure 1 shows the spectral distribution of a typical second surface aluminum mirror. The wavelength scale of this plot is greatly compressed and the reflectance scale expanded to emphasize the absorption features. Note that the absorption band at 800 nm is an inherent characteristic of aluminum mirrors. The small absorption bands near 1400 nm and 2200 nm are absorption features of the fused-quartz plate that protects the aluminum coating.

SRM 2023 can be cleaned by wiping the quartz first surface of the mirror with a soft tissue and isopropyl alcohol followed by a rinse with distilled water.

The research and development of this SRM was supported by the DoE Solar Thermal Program through the Solar Energy Research Institute. The calibration and certification were done by the Spectrophotometry Group of the Radiometric Physics Division. The overall direction and coordination of the preparation and technical measurements leading to the certification were performed under the chairmanship of J. C. Richmond.

The technical and support aspects involved in the certification and issuance of this SRM were coordinated through the Office of Standard Reference Materials by R. K. Kirby.

Washington, D.C. 20234
April 16, 1981

(over)

George A. Uriano, Chief
Office of Standard Reference Materials

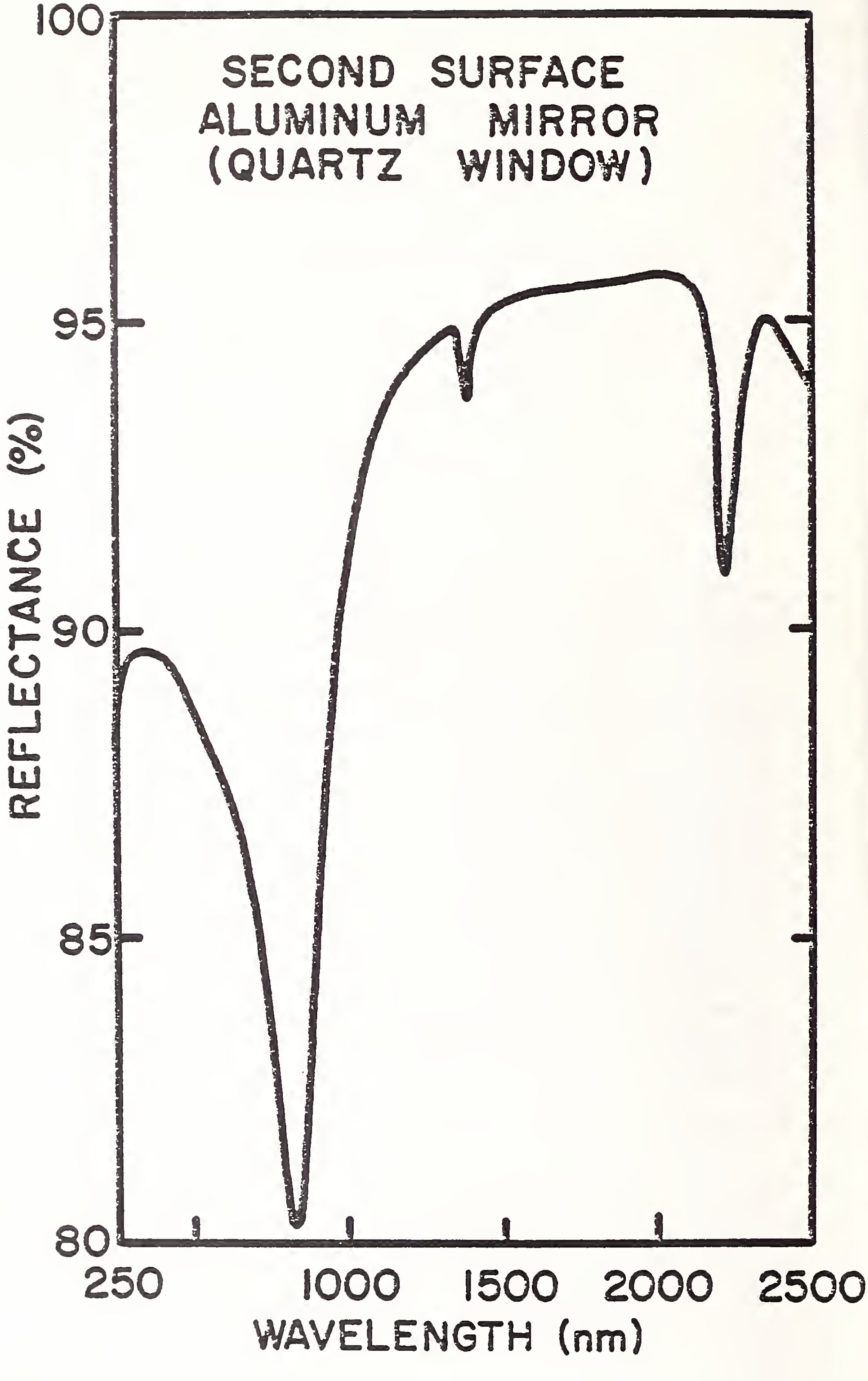
SECOND SURFACE
ALUMINUM MIRROR
(QUARTZ WINDOW)
REFLECTANCE (%)
100
95
90
85
80
250
1000
1500
2000
2500
WAVELENGTH (nm)

Table 1

Second Surface Mirror No. 124

(6° Incidence)

Wavelength (nm)	Reflectance
250	0.895
300	.891
350	.892
400	.893
450	.887
500	.884
550	.878
600	.874
632.8	.867
650	.863
700	.852
750	.833
800	.805
850	.800
900	.846
1000	.910
1060	.924
1100	.932
1200	.942
1300	.946
1500	.952
1750	.955
2000	.953
2250	.870
2500	.897

Table 2

The spectral reflectance of a typical second surface mirror as a function of wavelength, angle of incidence, and polarization.

(These values are not certified)

Wavelength and Angle of Incidence	Parallel(p) Polarized	Perpendicular(s) Polarized	Unpolarized (Ordinary)
250 nm			
6°	0.881	0.882	0.8815
30°	.872	.886	.879
45°	.862	.889	.8755
300 nm			
6°	.897	.897	.897
30°	.889	.902	.8955
45°	.880	.908	.894
400 nm			
6°	.895	.896	.8955
30°	.888	.902	.895
45°	.880	.908	.894
600 nm			
6°	.874	.876	.875
30°	.868	.884	.876
45°	.858	.892	.875
800 nm			
6°	.808	.810	.809
30°	.797	.820	.8085
45°	.782	.833	.8075
1000 nm			
6°	.910	.911	.9105
30°	.908	.918	.913
45°	.902	.924	.913
1500 nm			
6°	.952	.953	.9525
30°	.953	.958	.9555
45°	.951	.962	.9565
2000 nm			
6°	.954	.955	9545
30°	.956	.961	.9585
45°	.955	.964	.9595
2500 nm			
6°	.920	.918	.919
30°	.921	.929	.925
45°	.918	.927	.9225

Secretary

Bureau of Standards
Ambler, Director

National Bureau of Standards

Certificate

Standard Reference Material 2024

Second Surface Aluminum Mirror for Specular Reflectance from 250 to 2500 nm

V. R. Weidner and J. J. Hsia

iis Standard Reference Material (SRM) is intended for use in calibrating the photometric scale of specular reflecto-eters. SRM 2024 is 2.5 x 10.1 cm in size. The aluminum mirror is vacuum deposited on the surface of a 2-mm thick sed-quartz plate. This mirror is protected by a second fused-quartz plate attached to the first plate with epoxy cement.

ie specular reflectance of the mirror was measured at 50-nm intervals from 250 nm to 900 nm, at 100-nm intervals from)0 nm to 1300 nm; and at 250-nm intervals from 1500 nm to 2500 nm. In addition to these wavelengths, the reflectance as also measured at the laser wavelengths 632.8 nm and 1060 nm.

ie certified values were determined in the following way: The reflectance of a master mirror was measured at the above ecified wavelengths with a highly accurate specular reflectometer-spectrophotometer at angles of incidence of 6°, 30°, id 45°. These measurements were made for both vertically and horizontally polarized incident beams. The overall icertainty of these measurements is ±0.2 percent. The specular reflectance of the SRM second surface mirror was easured relative to the master mirror on a high-precision reflectometer for 6° incidence only. The certified values of ecular reflectance for the SRM mirror is based on the average value of the vertical and horizontal polarizations for the aster mirror at 6° incidence. The certified values listed in Table 1 are assigned an uncertainty of ± 0.005. The uncertified ta listed in Table 2 indicate the variation in the specular reflectance of a typical second surface SRM mirror as a nction of angle of incidence and plane of polarization. Figure 1 shows the spectral distribution of a typical second rface aluminum mirror. The wavelength scale of this plot is greatly compressed and the reflectance scale expanded to iphasize the absorption features. Note that the absorption band at 800 nm is an inherent characteristic of aluminum irrors. The small absorption bands near 1400 nm and 2200 nm are absorption features of the fused-quartz plate that otects the aluminum coating.

M 2024 can be cleaned by wiping the quartz first surface of the mirror with a soft tissue and isopropyl alcohol followed a rinse with distilled water.

ie research and development of this SRM was supported by the DoE Solar Thermal Program through the Solar iergy Research Institute. The calibration and certification were done by the Spectrophotometry Group of the idiometric Physics Division. The overall direction and coordination of the preparation and technical measurements iding to the certification were performed under the chairmanship of J. C. Richmond.

ie technical and support aspects involved in the certification and issuance of this SRM were coordinated through the fice of Standard Reference Materials by R. K. Kirby.

ashington, D.C. 20234
)ril 16, 1981

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George A. Uriano, Chief
Office of Standard Reference Materials

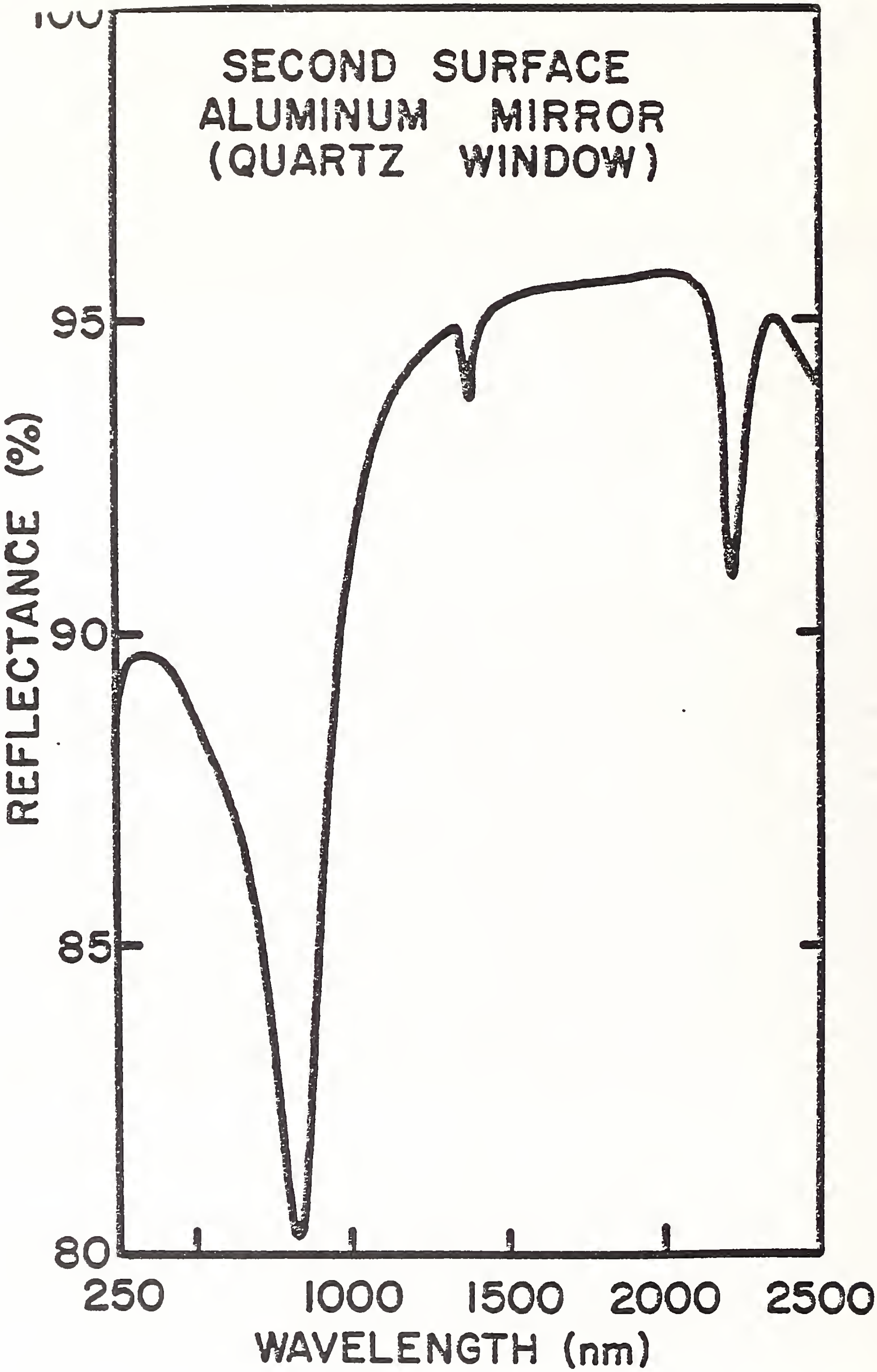
SECOND SURFACE
ALUMINUM MIRROR
(QUARTZ WINDOW)
95
90
85
80
REFLECTANCE (%)
250
1000
1500
2000
2500
WAVELENGTH (nm)

Table 1

Second Surface Mirror No. 29

(6° Incidence)

Wavelength (nm)	Reflectance
250	0.880
300	.894
350	.894
400	.893
450	.889
500	.885
550	.879
600	.873
632.8	.869
650	.865
700	.853
750	.834
800	.807
850	.801
900	.847
1000	.911
1060	.926
1100	.933
1200	.942
1300	.947
1500	.952
1750	.955
2000	.954
2250	.895
2500	.911

Table 2

The spectral reflectance of a typical second surface mirror as a function of wavelength, angle of incidence, and polarization.

(These values are not certified)

Wavelength and Angle of Incidence	Parallel(p) Polarized	Perpendicular(s) Polarized	Unpolarized (Ordinary)
250 nm			
6°	0.881	0.882	0.8815
30°	.872	.886	.879
45°	.862	.889	.8755
300 nm			
6°	.897	.897	.897
30°	.889	.902	.8955
45°	.880	.908	.894
400 nm			
6°	.895	.896	.8955
30°	.888	.902	.895
45°	.880	.908	.894
600 nm			
6°	.874	.876	.875
30°	.868	.884	.876
45°	.858	.892	.875
800 nm			
6°	.808	.810	.809
30°	.797	.820	.8085
45°	.782	.833	.8075
1000 nm			
6°	.910	.911	.9105
30°	.908	.918	.913
45°	.902	.924	.913
1500 nm			
6°	.952	.953	.9525
30°	.953	.958	.9555
45°	.951	.962	.9565
2000 nm			
6°	.954	.955	9545
30°	.956	.961	.9585
45°	.955	.964	.9595
2500 nm			
6°	.920	.918	.919
30°	.921	.929	.925
45°	.918	.927	.9225

Secretary
Bureau of Standards
Ambler, Director

National Bureau of Standards

Certificate

Standard Reference Material 2025

Second Surface Aluminum Mirror with Wedge for Specular Reflectance from 250 to 2500 nm

V.R. Weidner and J.J. Hsia

his Standard Reference Material (SRM) is intended for use in calibrating the photometric scale of specular reflecto-eters. The aluminum mirror has been vacuum deposited on the back surface of a 2-mm thick optical quality vitreous ıartz plate that has a wedge of 10 mrad (0.573°) between its long faces. This mirror is protected by a second vitreous ıartz plate with a similar wedge that is cemented to the first plate in such a way that the front and back surfaces of the irror are parallel to 10 μm.

'hen a collimated beam is incident to the first surface at −6°, beams are reflected at 6°, ~7.6°, ~9.3°, ~11.0°, etc. ssentially all of the reflected flux is contained in the first four beams. The angle of reflection is a function of both the edge angle and its dispersion (which is a function of wavelength). Calibration of photometers can be accomplished by ing any of the individual beams or by using the total reflectance. Only the first reflected beam and the total reflectance, owever, are certified.

he specular spectral reflectance of a master second-surface mirror was measured at 25 wavelengths with a high-accuracy ecular spectral reflectometer at 6° incidence. The first surface reflectance, ρ_1, of an uncoated plate was also measured ith the same instrument at 6° incidence, with a detector that received only the beam reflected from the first surface. As e plate that was used for this SRM was cut from the same piece of optical quality vitreous quartz (and had identical olishing treatment) as the uncoated plate, it is assumed that the reflectance from the first surface is the same, within the ncertainty of the certified value. The 6°-hemispherical reflectance of this SRM was compared to that of the master andard at the same 25 wavelenghts with a high-precision integrating sphere reflectometer. The measured reflectance tio was multiplied by the known reflectance of the standard at each wavelength to obtain the ρ_t spectral data reported in able 1. The overall uncertainty of these measurements is ± 0.5 percent.

ne Figure shows the spectral distribution of a typical second surface aluminum mirror. The wavelength scale of this plot greatly compressed and the reflectance scale expanded to emphasize the absorption features. Note that the absorption ınd at 800 nm is an inherent characteristic of aluminum mirrors.

RM 2025 can be cleaned by wiping the quartz first surface of the mirror with a soft tissue and isopropyl alcohol llowed by a rinse with distilled water.

ne calibration and certification were done by the Spectrophotometry Group of the Radiometric Physics Division. The erall direction and coordination of the preparation and technical measurements leading to the certification were rformed under the chairmanship of J.C. Richmond.

ne technical and support aspects involved in the certification and issuance of this SRM were coordinated through the ffice of Standard Reference Materials by R.K. Kirby.

'ashington, D.C. 20234
ebruary 23, 1982

George A. Uriano, Chief
Office of Standard Reference Materials

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of the equation for reflectance at normal incidence,

$$\rho_1 = \left(\frac{1-n}{1+n}\right)^2$$

These values are given in Table 2.

The angles of reflection for the first four beams reflected from the SRM were computed for each wavelength from the index of refraction. The plane of incidence is taken as a plane normal to the surface and parallel to the long sides of the mirror. All angles between normal and the thin end of the wedge are negative, and those between normal and the thick end are positive.

The direction θ_1 of the first beam, with reflectance ρ_1, is 6° since there is no refraction. The directions of the other three beams are:

$$\theta_2 = \sin^{-1}\left\{n \sin[2\alpha + \sin^{-1}(\tfrac{1}{n}\sin 6°)]\right\}$$
$$\theta_3 = \sin^{-1}\left\{n \sin[4\alpha + \sin^{-1}(\tfrac{1}{n}\sin 6°)]\right\}$$
$$\theta_4 = \sin^{-1}\left\{n \sin[6\alpha + \sin^{-1}(\tfrac{1}{n}\sin 6°)]\right\}$$

where $\alpha = 0.573°$.

These directions for each wavelength are given in Table 2.

Note that the angle of reflection is a function of both the wedge effect of the plate and its dispersion. The wedge effect is independent of wavelength. The dispersion angle changes with wavelength because the index of refraction of the plate changes with wavelength. If the wedge standards are used to calibrate a specular spectral reflectometer at different wavelengths, using beam 2 reflected once from the second-surface aluminum coating, the dispersion effect may make it necessary or desirable to shift the optical path slightly when changing wavelength. If spectrally total reflectance measurements are made, there will be a slight spread (about 0.1° for beam 2, 0.2° for beam 3 and about 0.35° for beam 4) in the reflected beam, due to the dispersion of the plate and a slightly larger detector may be required for spectrally total measurements than for spectral measurements.

Because pratically all of the flux reflected from the wedge is contained in the first four beams, the total specular reflectance, ρ_t, can be approximated in terms of the reflectance of the first surface, ρ_1, the transmittance of the quartz surface, $\tau = 1-\rho_1$, and the reflectance of the aluminum surface, ρ_s, as

$$\rho_t = \rho_1 + \tau_1^2\rho_s + \tau_1^2\rho_1\rho_s^2 + \tau_1^2\rho_1^2\rho_s^3$$

Using the measured values of ρ_t and ρ_1, the values of ρ_2, ρ_3, and ρ_4 can be calculated as

$$\rho_2 = \tau_1^2 \cdot \rho_s$$
$$\rho_3 = \tau_1^2 \cdot \rho_1 \cdot \rho_s^2$$
$$\rho_4 = \tau_1^2 \cdot \rho_1^2 \cdot \rho_s^3$$

where

$$\rho_s = \frac{\rho_t - \rho_1}{\tau_1^2 + \rho_1(\rho_t - \rho_1)}$$

The computed values for ρ_2, ρ_3, and ρ_4 are given in Table 3.

These equations were derived on the basis of two assumptions; (1) that there is no internal absorptance in the vitreous quartz (there is some slight absorptance at 250 nm, but essentially none at 300 nm and above); and (2) that the values of τ_1, ρ_1 and ρ_s are independent of the direction of incidence over the range of angles of incidence involved. This is essentially true for angles of incidence of less than 15°. The computed reflectance for a material with index of refraction of 1.5 is 0.040000 at normal incidence, 0.040002 at 6° incidence and 0.040081 at 15° incidence. The fractional error due to the assumption that the reflectance is independent of the angle of incidence is thus well within the uncertainty of the measured values.

Table 1

Total Specular Spectral Reflectance (ρ_t), for 6° Incidence, and First Surface Reflectance (ρ_1) of Fused Quartz Plate

Mirror No. 107W

Wavelength (nm)	(ρ_t)	(ρ_1)
250	0.869	0.0406
300	.894	.0379
350	.895	.0364
400	.893	.0355
450	.888	.0350
500	.884	.0347
550	.878	.0344
600	.874	.0342
632.8	.868	.0342
650	.865	.0342
700	.853	.0339
750	.835	.0338
800	.807	.0337
850	.800	.0335
900	.847	.0334
1000	.911	.0333
1060	.925	.0332
1100	.932	.0332
1200	.942	.0330
1300	.947	.0328
1500	.952	.0325
1750	.955	.0321
2000	.955	.0317
2250	.951	.0313
2500	.949	.0310

TABLE 2

Index of Refraction, n, of Cover Plate and Direction, in Degree from Normal, of First Four Reflected Beams

(These Values Are Not Certified)

Wavelength nm	Index of Refraction	Θ_1 deg.	Θ_2 deg.	Θ_3 deg.	Θ_4 deg.
250	1.5047	6.000	7.731	9.466	11.207
300	1.4834	6.000	7.707	9.417	11.132
350	1.4715	6.000	7.693	9.389	11.090
400	1.4643	6.000	7.684	9.372	11.065
450	1.4603	6.000	7.680	9.363	11.051
500	1.4578	6.000	7.677	9.357	11.042
550	1.4554	6.000	7.674	9.352	11.034
600	1.4538	6.000	7.672	9.348	11.028
632.8	1.4538	6.000	7.672	9.348	11.028
650	1.4538	6.000	7.672	9.348	11.028
700	1.4513	6.000	7.669	9.342	11.019
750	1.4505	6.000	7.668	9.340	11.017
800	1.4497	6.000	7.668	9.338	11.014
850	1.4481	6.000	7.666	9.335	11.008
900	1.4473	6.000	7.665	9.333	11.005
1000	1.4464	6.000	7.664	9.331	11.002
1060	1.4456	6.000	7.663	9.329	10.999
1100	1.4456	6.000	7.663	9.329	10.999
1200	1.4440	6.000	7.661	9.325	10.994
1300	1.4423	6.000	7.659	9.321	10.988
1500	1.4399	6.000	7.656	9.316	10.979
1750	1.4365	6.000	7.652	9.308	10.968
2000	1.4322	6.000	7.648	9.300	10.956
2250	1.4299	6.000	7.645	9.292	10.944
2500	1.4274	6.000	7.642	9.287	10.935

Table 3

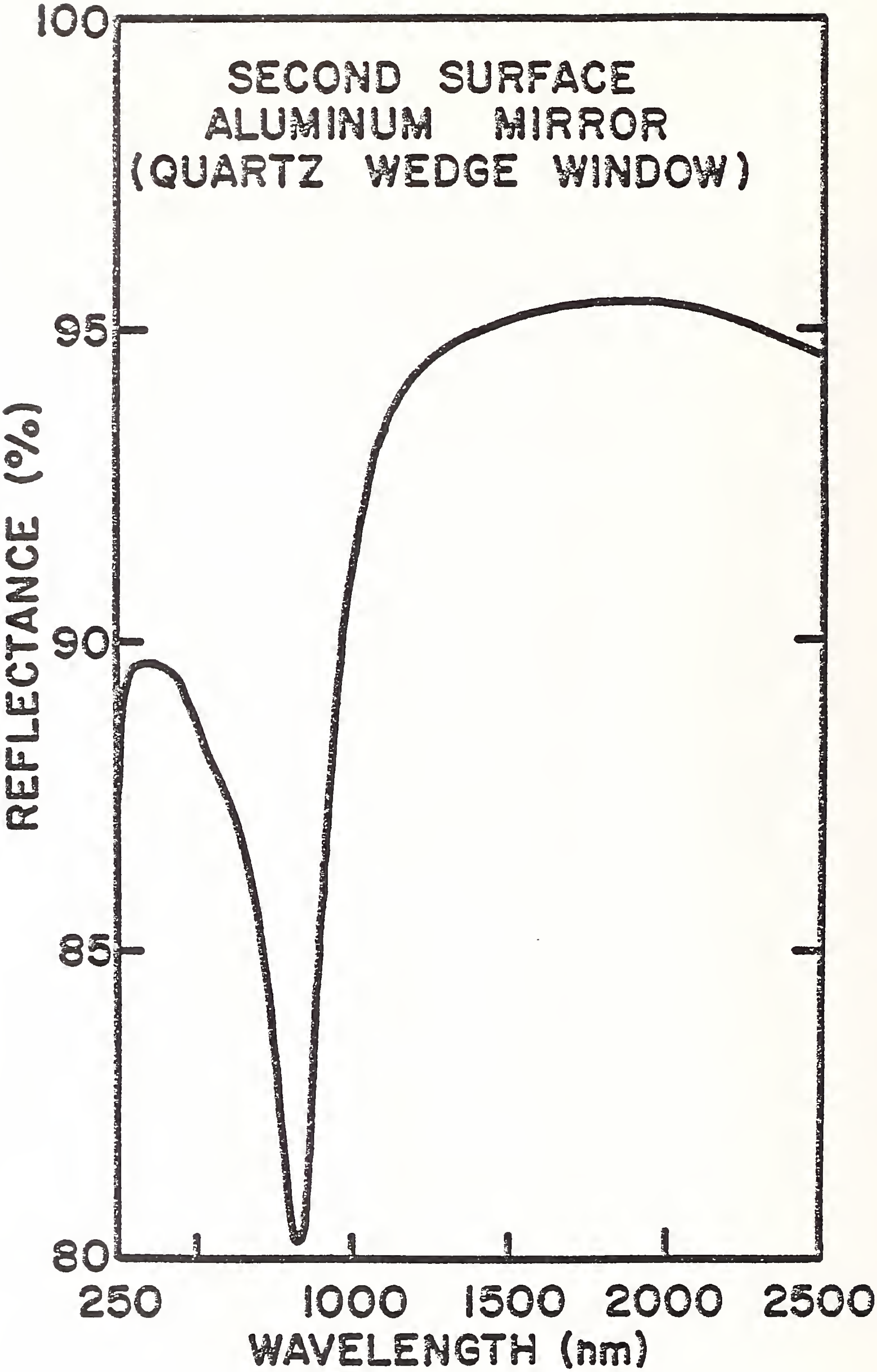
Reflectances ρ_2, ρ_3, and ρ_4

Reflected by the Wedge Mirrors, Computed from the Measured First Surface Reflectance of the Plate and the Total Specular Spectral Reflectance for a Collimated Beam Incident at -6°

(THESE VALUES ARE NOT CERTIFIED)

Mirror No. 107W

Wavelength (nm)	(ρ_2)	(ρ_3)	(ρ_4)
250	0.7992	0.0282	0.0010
300	.8271	.0280	.0009
350	.8306	.0270	.0009
400	.8303	.0263	.0008
450	.8265	.0257	.0008
500	.8233	.0252	.0008
550	.8181	.0247	.0007
600	.8147	.0243	.0007
632.8	.8091	.0240	.0007
650	.8062	.0238	.0007
700	.7954	.0230	.0007
750	.7786	.0219	.0006
800	.7523	.0204	.0006
850	.7460	.0200	.0005
900	.7906	.0223	.0006
1000	.8511	.0258	.0008
1060	.8644	.0265	.0008
1100	.8710	.0269	.0008
1200	.8807	.0274	.0009
1300	.8858	.0275	.0009
1500	.8911	.0276	.0009
1750	.8946	.0274	.0008
2000	.8954	.0271	.0008
2250	.8923	.0266	.0008
2500	.8911	.0262	.0008


SECOND SURFACE
ALUMINUM MIRROR
(QUARTZ WEDGE WINDOW)
100
95
90
85
80
REFLECTANCE (%)
250
1000
1500
2000
2500
WAVELENGTH (nm)

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5. AUTHOR(S)

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

NBS was requested by the Department of Energy to prepare, calibrate and disseminate standards of spectral specular reflectance for use in calibrating reflectometers used to evaluate the solar specular reflectance of concentrating mirrors used in solar energy systems.

The mirror chosen was a second-surface mirror of vacuum-deposited aluminum on optically polished vitreous quartz backed up with a second plate of ground and polished vitreous quartz cemented to the back of the mirror. Standards were prepared in two sizes, 51 x 51 mm, and 25 x 101 mm.

The cost of developing and calibrating the standards was included in a contract issued by the Solar Energy Research Institute of Golden, Colorado, which is financed by the Department of Energy.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

aluminum mirrors; directional specular reflectance; reflectance specular; reflectance standards; second surface mirrors; solar reflectance; specular spectral reflectance.

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